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THE RELATIONSHIP OF HARDNESS MEASUREMENTS TO THE TENSILE AND COMPRESSION FLOW CURVES

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GENERAL ELECTRIC RESEARCH LABORATORY

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NOTICES

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FOREWORD

This report was prepared by the General Electric Company Research Laboratory under United States Air Force Contract No. AF 33(616)-2120. This contract was initiated under Task 70627, "Deformation Mechanisms of Metals," a part of Project 7351, "Metallic Materials," and was administered under the direction of the Aeronautical Research Laboratory, Directorate of Research, Wright Air Development Center, with Major A. A. Marston as Task Scientist.

ABSTRACT

The approximation of a uniaxial tensile stress flow curve from hardness measurements is possible by utilizing certain empirical conversion constants. Agreement of the tensile and hardness testing methods is possible upon metals such as aluminum, copper, and steel. However, magnesium is not amenable to such a conversion of testing procedures. The presence of profuse twinning at low stress levels is believed to be the reason for unfavorable results in magnesium.

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PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER

Aldro Lingard

ALDRO LINGARD
Colonel, USAF
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Directorate of Research

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THE RELATIONSHIP OF HARDNESS MEASUREMENTS TO THE TENSILE AND COMPRESSION FLOW CURVES

R. E. Lenhart

INTRODUCTION

Hardness, in its most familiar connotation, is the resistance of a material to local indentation. When the size and depth of the indentation is measured, and the load that produced the indentation is specified, the hardness can be defined in a quantitative manner. The Brinell, Vickers, and Rockwell[1, 2, 3] hardness testing methods are the three most common procedures for obtaining quantitative hardness values upon metals. These testing machines impress either a hardened ball, a diamond pyramid, or a diamond cone into the metal. The results are essentially a measure of the resistance to plastic deformation of the metal by external forces.

The familiar uniaxial stress tensile test is also a measure of the resistance to plastic deformation of a metal by external forces. The relationship of the hardness to the tensile method of producing plastic deformation has in general been ill-defined. The complex nature of the stress distribution during plastic flow in the hardness test precludes a simply derived relationship to the tensile test. However, Tabor[4, 5, 6] has developed an empirical correlation that relates the two and enables a conversion of one measurement to the other. The usefulness of this correlation depends upon its exactitudes and its limitations. This report presents data intended to corroborate the work of Tabor and to specify a major limitation of his empirical correlation.

BACKGROUND

The mean pressure between the surface of the indenter and the indented metal is equal to the ratio of the load to the projected area of the indentation. Meyer, in 1908, was the first to propose this relationship, and it is now referred to as the Meyer hardness. Thus,

$$Hm = \frac{4W}{\pi d^2} , \qquad (1)$$

where, Hm is the Meyer hardness number, W is the applied load, and d is the diameter of the indention. It is interesting to note that the Meyer hardness has the dimensions of stress.

The relationship between the load W and the size of the indentation d was also expressed by Meyer as,

$$W = kd^n . \tag{2}$$

Here, k and n are material constants. The value of n is generally greater than 2 and usually lies between 2 and 2.5. It is found that for fully annealed metals, n has a value near 2.5 while for fully work hardened materials it is close to 2.

The true stress-strain curve for metals may be approximated over an appreciable range of deformation by[7]

$$\sigma = ge^m , \tag{3}$$

where, g and m are constants and σ and e are the stress and strain respectively. The value of m usually lies between zero and 0.5 with annealed cubic materials being close to the upper value. This equation has been referred to as the "mechanical equation of state" and is expounded in detail by Hollomon and Lubahn.[8] If Eq. (2) is substituted into Eq. (1) then

$$Hm = \frac{4kd^n}{\pi d^2} = k_1 d^{n-2} , \tag{4}$$

where $k_1 = \frac{4k}{\pi}$. Examination of Eqs. (3) and (4) reveals that both are suitable for defining the plastic properties of metals. Both equations are of the exponential form with the exponents being nearly equal. However, the relationship between σ and Hm and between e and d being undefined precludes free substitution of one equation into the other. For example, Eq. (3) has the limitation of constant strain rate which is not maintained on a hardness test. As previously mentioned, Tabor has approached this problem by obtaining empirical constants that relate these variables. Readers are referred to his works for the details of his experiments that have produced the following equations.

$$Hm = 2.8\ \sigma \tag{5}$$

$$e = 0.2\ \frac{d}{D}\ , \tag{6}$$

where D is the diameter of the indenting ball.

The concept of tensile flow curves being derived from hardness measurements is of interest from at least two viewpoints. First, the preparation and testing of a hardness specimen requires much less expense and time than the tensile specimen. This point is of particular benefit to large alloy exploration programs. Secondly, flow curves could be obtained upon castings and other structures without the destruction of the component. This feature is attractive from a production expense viewpoint. The work presented in this report was initiated for the purpose of using the Tabor hardness relationships in a magnesium alloy exploration program. Thus it was desired to obtain experimental verification of the hardness tensile relationship for these alloys.

EXPERIMENTAL PROCEDURES AND RESULTS

The experiments reported herein were performed upon the magnesium-aluminum alloys described in a previous report.[9] The preparation of the alloys together with the tensile and compression testing are identical with that previously reported.

Specimens for the Meyer hardness procedure were prepared with dimensions 3 x 1/2 x 3/8 inches. The testing was performed upon a hand operated Brinell hardness tester with a load application duration of 15 seconds. Carapella and Shaw[10] discuss the importance of load application time, specimen size, load, and load application rate. Each of the factors influences the hardness value to a limited extent. However, each was held nearly constant for the obtaining of these data and was not considered to be a factor that would invalidate the results.

Figures 1 through 3 are typical of the tensile, compression, and hardness flow curves upon the various magnesium alloys. The hardness flow curves were obtained from Eqs. (5) and (6). Examination of Figs. 1 through 3 clearly shows that there is little similitude among the three types of flow curves. Figures 4 and 5 are data for Dural (24-ST6) aluminum and OFHC copper. These data were taken to demonstrate that the lack of agreement among testing procedures upon magnesium was a function of the material and not of the mechanical test. Although the Dural and OFHC curves in Figs. 4 and 5 are not exact duplicates, their juxtaposition is considerably better than shown in Figs. 1 to 3.

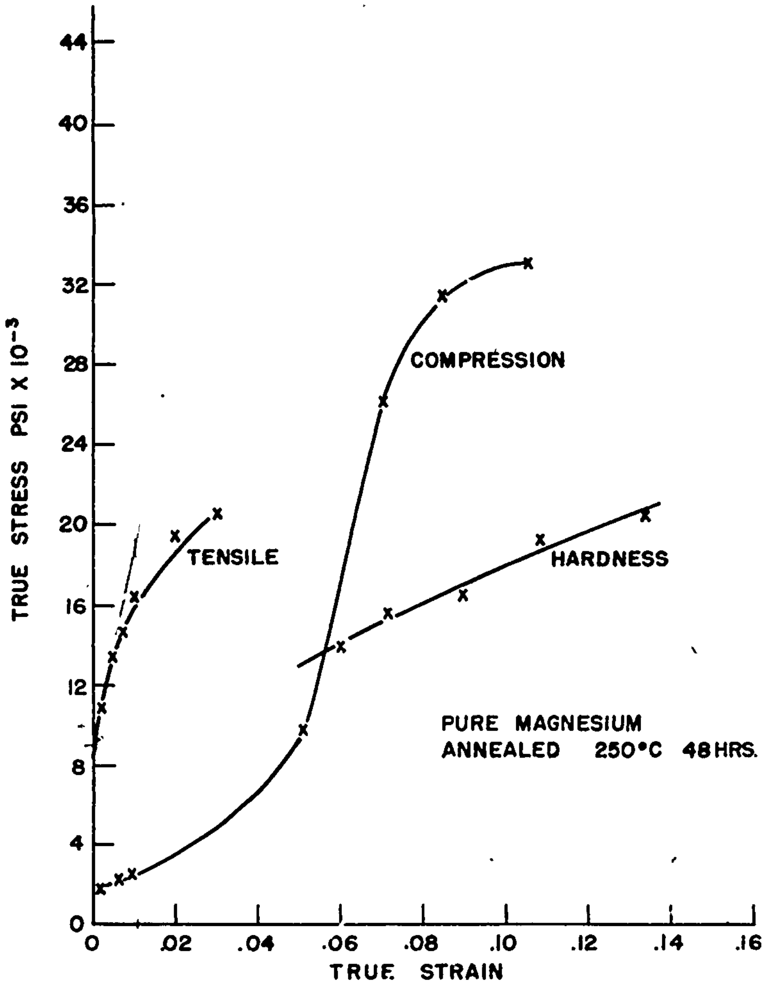

Fig. 1 True stress-true strain flow curves obtained upon pure magnesium.

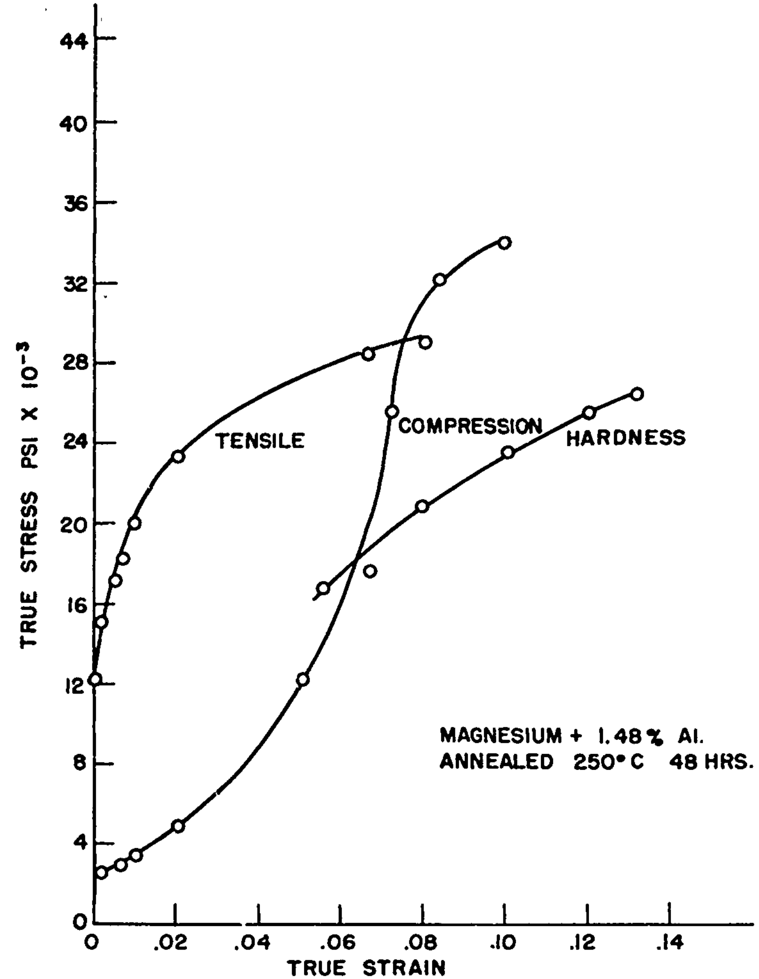

Fig. 2 True stress-true strain flow curves obtained upon magnesium plus 1.48 per cent aluminum.

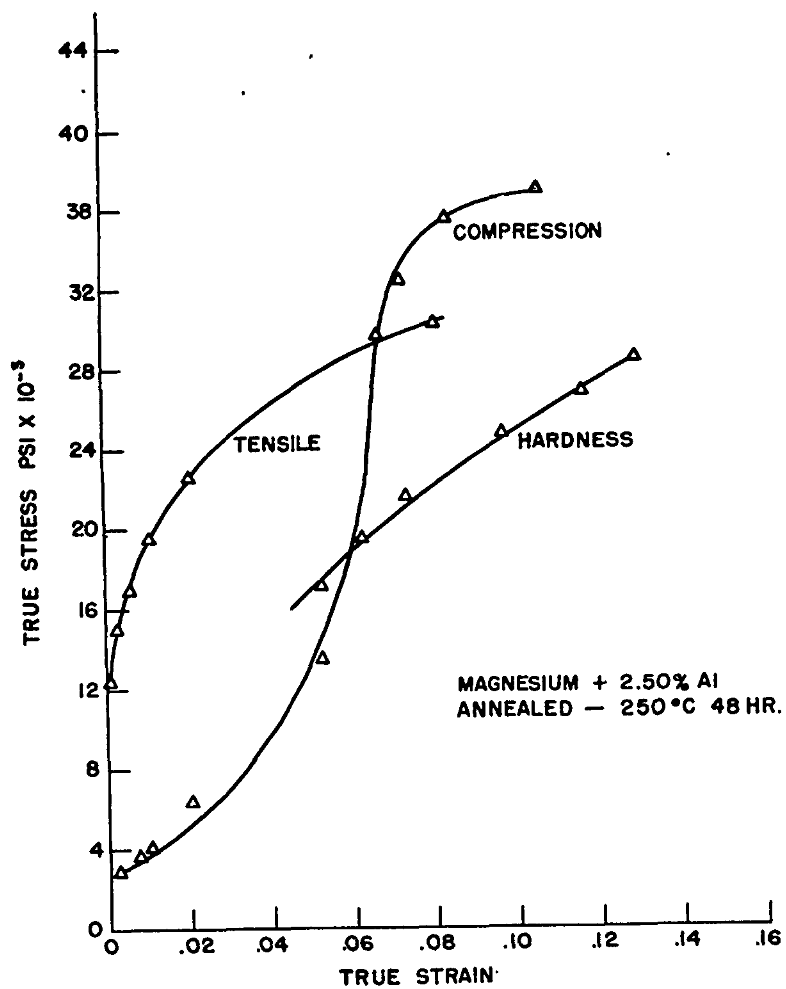

Fig. 3 True stress-true strain flow curves obtained upon magnesium plus 2.50 per cent aluminum.

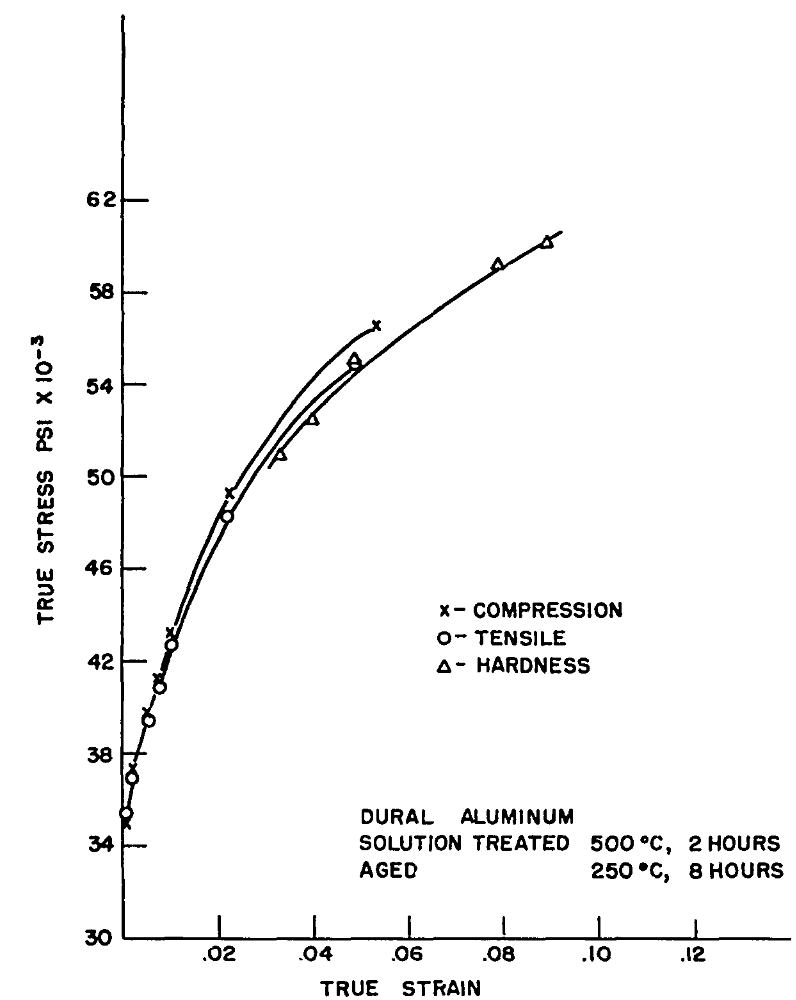

Fig. 4 True stress-true strain flow curves obtained upon Dural aluminum.

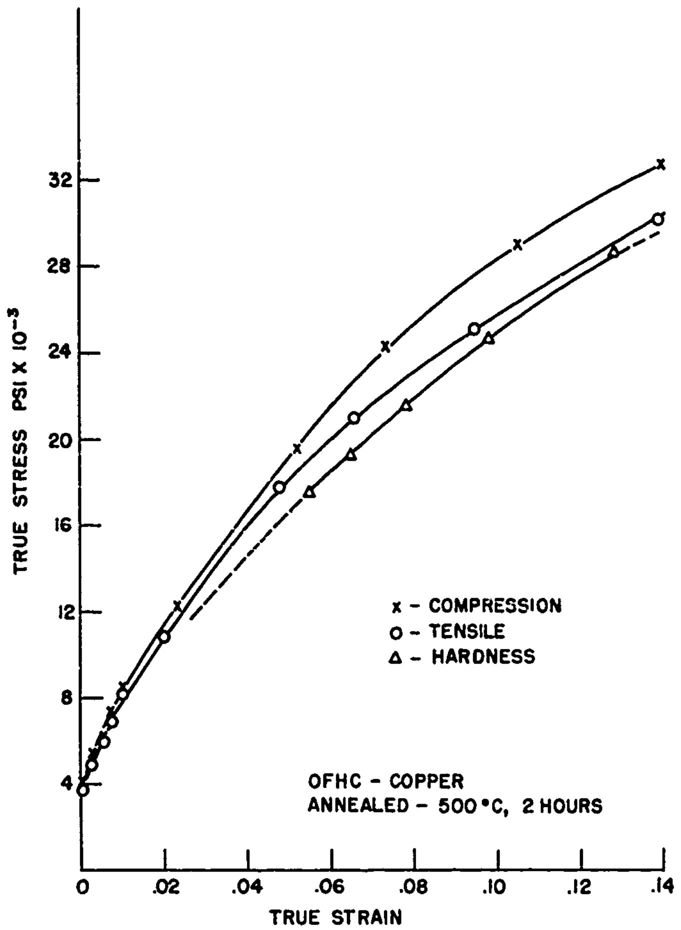

Fig. 5 True stress-true strain flow curves obtained upon OFHC copper.

Figure 6 is a graph that Tabor has published relating hardness to tensile flow curves upon three materials. The good agreement between testing methods is obvious in these graphs.

DISCUSSION

The results presented in Figs. 4, 5, and 6 demonstrate that the constants for conversion of hardness to tensile data formulated by Tabor are workable for aluminum, copper, and steel. The experimental error was in general less than 5 per cent between the two test methods. The same magnitude of difference appears between the results of the tensile and compressive tests.

The most obvious reasons that may be offered to explain the lack of testing agreement are experimental error, the Bauschinger effect, and crystal anisotropy. The exact contributions of each to the total difference would require a more detailed experimental program. Carapella and Shaw(10) point out that experimental error can be introduced in the hardness test if certain specimen dimension ratios are not controlled. These are:

(1) Specimen thickness should be at least 7 times the depth of the ball impression,

(2) Distance between the impression and the edge of specimen should be at least 2 times the diameter, and

(3) Distance between impressions should be at least 4 times the diameter.

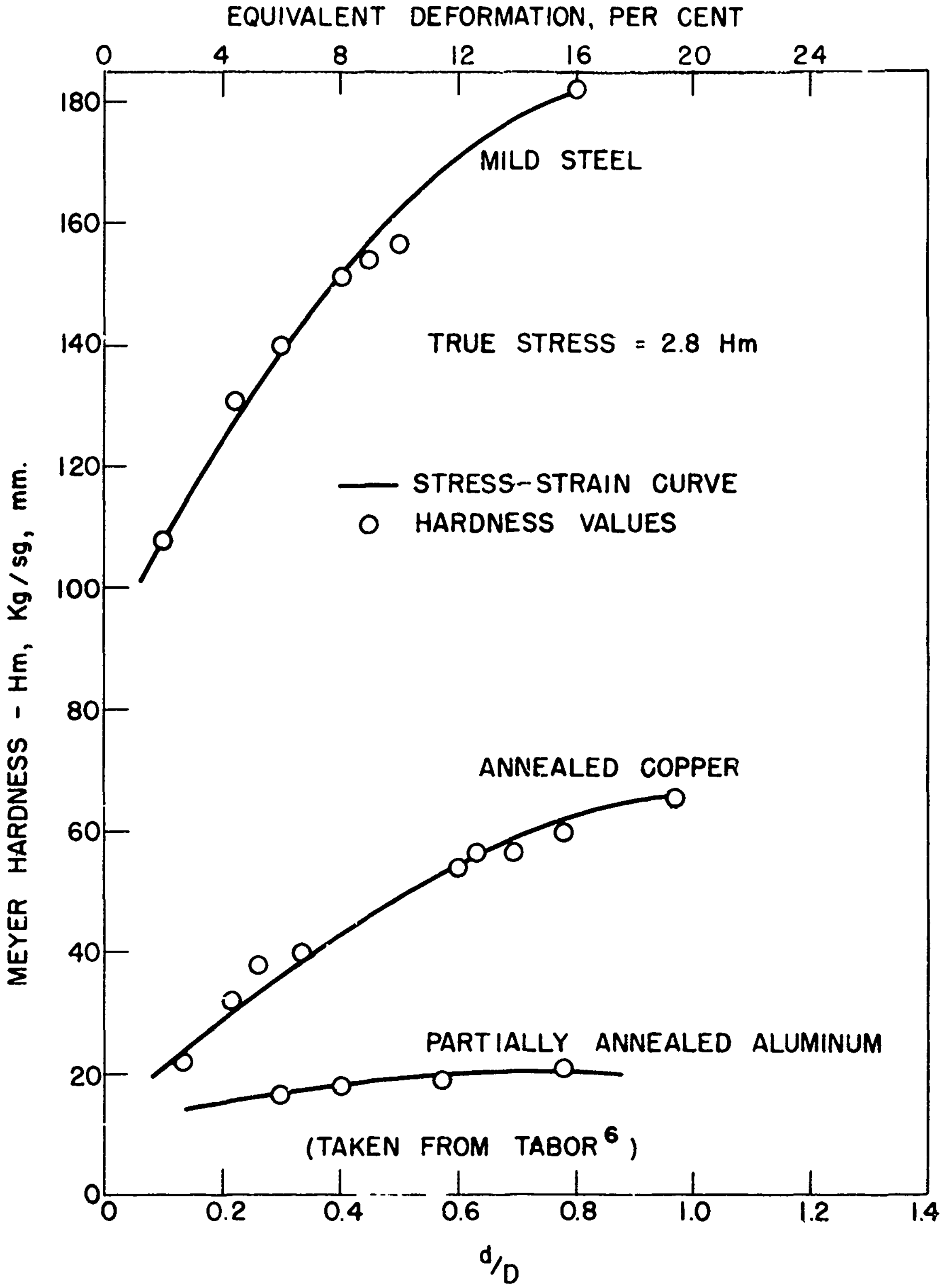

Fig. 6 Flow curves obtained by Tabor(6) upon steel, copper, and aluminum.

The Bauschinger effect can introduce error by lowering the compressive yield strength of a material that has undergone previous tensile plastic deformation (i.e., cold rolling). The third possible source of error is the crystalline anisotropy and its effect upon deformation. The magnitude of this error is strikingly demonstrated in Figs. 1 to 3 of this report. The explanation of this anisotropy error is contained in the plastic deformational characteristics of magnesium. Magnesium will deform by two main mechanisms, namely, slip and twinning. It is known [see Beck[11]] that twinning will not occur in single crystals when the applied stress axis is within certain regions of the crystalline orientation. Likewise, it is known that the magnitude of the critical resolved shear stress to produce slip varies by orders of magnitude as a function of angle between stress axis and crystalline orientation.[11] These factors combine to predict many different stress-strain relationships for single crystals of magnesium. Polycrystalline magnesium that possesses a high degree of preferred orientation should exhibit many of the same general stress-strain deviations.

Reviewing the data of this report, with respect to the three error factors just mentioned, it is possible to justify qualitatively certain discrepancies in the data. By utilizing the information presented in the previous report[9] upon the deformation of the magnesium alloys, the position of the magnesium hardness flow curve can be rationalized. The magnesium alloys had a preferred orientation with the basal plane (0001) parallel to the surface of the sheet. This orientation and the method of preparing specimens placed the compression and tensile test axis parallel to the basal plane. The hardness test axis was perpendicular to the basal plane. It was demonstrated[9] that the low yield strength and the shape of compression flow curve is associated with profuse twinning and that twinning is absent in the tensile test when a higher yield strength results. If the hardness test consisted of only compressive stress directly under the indenter so that no twinning occurred, one would expect the hardness flow curve to parallel the tensile flow curve. This criterion is based on the relationship of the hardness compression stress axis to the axis of the basal plane. However, the nature of the stress distribution under the hardness indenter is quite complex and results in compressive stresses throughout a hemispherical solid angle under the indenter. This stress distribution places a component of the compressive stress parallel to the basal plane of the magnesium during the hardness test. This stress state is somewhat analogous to bending, which results in profuse twinning in magnesium. Thus, there exists the necessary conditions to produce twinning. As a result, the hardness flow curve would be expected to lie intermediate to the compressive and tensile flow curves and nearer to the compression curve. Metallographic examination of the magnesium under the hardness indentation reveals large amounts of twinning that seem to support the existence of lateral compressive forces under the indenter. Therefore, the ability of hardness measurements to predict tensile flow characteristics in magnesium was not possible because of the strong influence of twinning upon the deformational stress-strain relationships.

Such crystalline anisotropy is not found in copper and aluminum as is evident in magnesium. Both copper and aluminum are face-centered-cubic in structure and are not amenable to the formation of deformation twins. In addition they possess several possible slip planes rather than just one, as exhibited by magnesium at room temperature. As a result, one should expect similitude among the deformation flow curves. The flow curves on Dural, Fig. 4, are considered quite good and within normal scatter of data. The data on OFHC copper, Fig. 5, possess more scatter but not enough to invalidate the tests. It will be noted that Tabor's data on copper, Fig. 6, possess scatter of similar magnitude. Just why copper should give such results is not clear. However, the ability to correlate hardness and tensile data is still quite good.

The importance of the Bauschinger effect and experimental error in these data is unresolved. Since the alloys were annealed between the rolling and the testing, the Bauschinger effect should be small. The data tend to confirm this statement by the sameness of compression and tensile yield points in the copper and aluminum. Experimental error is possible in all of the high strain hardness tests, since a ratio of 7:1 between sample height and hardness depth was not maintained. However, this condition should only apply to the last one or two data points of each hardness flow curve. The data do not indicate that there is significant error in that region. Therefore, it can be concluded that the data are reliable.

CONCLUSIONS

In general, Tabor's correlation between the hardness test and tensile test is reasonable and workable. However, care must be exercised to reduce experimental error and the Bauschinger effect. From the experimental evidence presented here upon magnesium, Tabor's correlation should not be applied to metals that are subject to large deformation mechanism anisotropies, such as twinning.

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